Temperatures below one degree Kelvin

C. J. GORTER

Vol. 82, No. 3

Proceedings of the American Academy of Arts and Sciences

Temperatures below 1° K*

C. J. Gorter

Kamerlingh Onnes Laboratory, Leiden

Historically the notion of temperature has two very different theoretical backgrounds. One of these backgrounds, connected with the kinetic theory of gases, as it was developed in the 19th century by *Clausius* and *Maxwell*, has to do with the random motions of molecules and atoms. According to its central statement the absolute or Kelvin temperature is proportional to the average kinetic energy of free molecules. This statement is obviously not applicable if we admit interactions between the molecules, such as exist in a real gas or, much more intimately, in a liquid or a solid. What then remains is a somewhat more complicated connection between the probability for a system of particles to find itself in a particular state of energy and the Kelvin temperature, a connection given by the so-called *Boltzmann* distribution factor which tells us that on the average low energy states are occupied more frequently than high energy states, but that the higher energies occur more frequently the higher the temperature is.

The second background, created somewhat earlier in the 19th century by *Carnot* and *Kelvin*, has an industrial origin. It has to do with the maximum efficiency of engines or motors which transform heat into mechanical energy as well as of refrigerating machines. These engines, motors and refrigerating machines operate between a low temperature T_l and a high temperature T_h. The engines and motors take up the heat Q_h at the higher temperature T_h and give off a smaller amount of heat Q_l at the lower temperature T_l while the refrigerating machines, on the contrary, absorb heat at the lower temperature, giving off a larger amount at the higher temperature. In both cases the difference is made up by potential energy or work, delivered in the first case and consumed in the case of the refrigerating machine. Now, according to *Carnot* and *Kelvin*, the cyclic process has its maximum efficiency if the ratio of the two temperatures and the two amounts of heat

*Communication presented at the 1360th meeting of the American Academy of Arts and Sciences, Boston, October 15, 1952.

is equal: $T_h/T_l = Q_h/Q_l$. In fact this maximum efficiency is reached when all frictional losses are avoided.

It has been the achievement of *Boltzmann*, *Gibbs* and *Ehrenfest* in the end of the 19th and in the beginning of the 20th century, to show that the kinetic and the thermodynamical backgrounds are in complete agreement with each other as long as usually insignificant fluctuation processes are neglected. Thanks to them we may now use the two backgrounds and their mathematical formalisms alternatingly and at will without being afraid of internal contradictions.

It is one of the most essential qualities of temperature that, in a system which is left to itself, it tends to become uniform. Thus a thermometer placed in a bath accepts soon its temperature.

Historically the drive to ever lower and lower temperatures was realized in steps, and even in the most modern engines to obtain very low temperatures these, or similar, steps are repeated. Starting from the housewives' temperature interval between 273°K and 373°K, the first step is to the liquid air region between 60° to 90°K; next comes the liquid hydrogen interval from 14° to 20°K and the liquid helium region between 4.2°K and about 1.0°K and finally the region of tonight's subject: that obtainable by adiabatic demagnetization from 1°K to perhaps 0.001°K or further downwards. Seen on the usual linear temperature scale, the steps become smaller and smaller and the achievement may seem of less and less importance. However, the fact that in the thermo-dynamical background we have essentially to do with ratios of absolute temperatures instead of with differences, just as sometimes occurs in the physiological response on excitation, encourages us to introduce a logarithmic temperature scale in analogy to the well known decibel system of acoustics. It is clear that such a scale, according to which the liquid helium interval and the range attainable by adiabatic demagnetization easily outweigh the more usual temperature ranges, appeals to the vanity of the low temperature physicist, but he has to admit that this logarithmic scale, which suggests that a temperature interval between 0.1 and 0.01°K is as important as that between 100° and 1000°K, is only fair and adequate in the study of certain specific properties of matter. In accordance with *Nernst's* law many properties of matter, among which I mention the density, the

heat of vaporization, the elastic and dielectric properties, do not change materially at very low temperatures. But the electrical conductivity, the heat conductivity and paramagnetism do. Of those the paramagnetic properties are of prime importance for the low temperature physicist since they have to do with essentially reversible phenomena, and thus may be used in refrigerating processes.

The mechanisms used in the first steps of the downward drive are of two different natures. They either aim directly at a decrease of the kinetic energy of random motions inside a system or at an increase of its potential energy at the expense of the kinetic energy.

In order to make the mechanisms of these processes somewhat more familiar to the non-physicists in the present audience, let us compare the kinetic energy of particles to cash money belonging to individuals and their potential energy to their bank accounts. The aim of the low temperature physicist is to reduce the cash and he can do this either directly, by taxing and other means, or by persuading the individuals to increase their bank accounts at the expense of their available cash. When a gas expands, while doing work, the molecules strike a backward moving piston, coming back at reduced velocity, part of their kinetic energy thus having been taxed away. If the temperature on the contrary is reduced by evaporating a liquid adiabatically, as in the usual household refrigerators, or by expanding a gas through a nozzle, the kinetic energy of the molecules decreases because of their increasing potential energy. In order to obtain a repeatable closed cycle it will be necessary to compress the gas or to condense the vapour beforehand or afterwards, while leading away the heat that is then developed. The decrease in cash is caused at the moment when the individuals are persuaded to increase their bank accounts. If one wishes to obtain a continuously working cyclic process it will be necessary to have the cash money spent when, in another phase of the cycle, it is plentiful. The magnetic process invented by *Debye* and *Giauque* to produce cold at temperatures under 1°K is analogous to the last mentioned methods of producing cold by evaporating a liquid. The required increase of potential energy, however, is not obtained by an increase of distance between the individual molecules but rather by an increase of the

magnetic energy connected with the presence of an electromagnet. So far, because of experimental difficulties, very few attempts have been made to work in a repeatable closed cycle and the usual procedure to reduce the kinetic energy consists of only one decrease and one subsequent increase of the potential energy, or the bank accounts if you wish. Thus first the permitted bank accounts are made to differ so considerably that nearly all individuals have to choose the lower one of the accounts. Then it is necessary to wait till the cash, that has been paid out, is largely spent. Subsequently the differences between the permitted bank accounts are reduced drastically, thus luring the individuals to place their scarce remaining cash in the bank. The magnetic process thus consists of first subjecting a paramagnetic substance such as chromium or iron alum, containing many magnetic ions, to a high magnetic field. The large majority of the ionic magnets then place themselves parallel with the field, thus reducing their potential energy and developing heat which is carried away to a bath of liquid helium which is in thermal contact with the substance. Then the substance is thermally insulated from the helium bath and the magnetic field switched off. During this adiabatic demagnetization, the elementary magnets then try to reassume their original random orientations by reducing all other energies available and thus cooling the substance down.

The next problem which then faces the low temperature physicist is the determination of the very low temperature thus obtained in his sample. This is carried out by performing a thermodynamic cyclic process with the sample and applying the central relation of our second background: $T_h/T_l = Q_h/Q_l$. After reaching the temperature T_l by adiabatic demagnetization a small amount of heat Q_l is introduced. Then the substance is remagnetized up to the original field. The temperature is then slightly higher than the original one and by extracting the amount of heat Q_h that original temperature is restored and the cycle thus closed. If our higher temperature T_h, which is in the neighborhood of 1°K, is known and the Q_h and Q_l are measured, we can thus calculate the unknown lower temperature T_l. The chief experimental problem is how the amount of heat Q_l is to be applied and measured. In Oxford this is done by irradiation with gamma rays and in Leiden by magnetic methods.

The magnetic properties of the cooling substance may be used as provisional thermometers and, by carrying out cyclic processes as sketched, we may obtain a calibration of these provisional thermometers on the Kelvin scale. The lowest temperature measured so far was 1.4 millidegree Kelvin in a mixed crystalline sample of chromium and aluminum alum.

The first scientific result of the experiments is of course the determination of the magnetic properties of the cooling substance itself. It is found that at sharply defined temperatures of a few centidegrees or millidegrees Kelvin the salts of the iron group, which are used, undergo a so-called transformation of the second kind and become anti-ferromagnetic or perhaps ferromagnetic. The individual magnets then have lost their individual freedom and form more or less rigid patterns of an antiparallel or parallel character. They rapidly lose the possibility to react independently on outside magnetic fields and on small temperature variations and either do not react at all or only co-operatively with many millions of their fellow magnets. If I were not afraid that pursuing our metaphor would lead us into the fields of sociology or even politics, I could work out how lack of cash may entail the loss of the individual liberty to react on changes in banking policy and thus lead to a social structure of a very rigid character, which differs widely from the paramagnetic way of life.

It will also be possible to cool other substances down and study their properties at the very low temperatures reached, though the slow tempo in which heat, or rather cold, is transported and transmitted at temperatures under 0.1°K often presents a serious obstacle. A few new superconductors have been discovered in this temperature region and their curves of magnetic disturbance have been determined. Furthermore a few provisional investigations have been carried out on the heat conductivity of various substances and on specific heats.

A most fascinating group of problems is connected with Helium II, the unruly liquid, probably existing as such down to the lowest temperatures, with its perhaps just as intriguing liquid isotope ^{3}He and with mixtures of these two liquids.

Another very promising scientific application of very low temperature physics is the orientation or alignment of atomic nuclei, and it may be appropriate to devote some attention to that topic.

It has been mentioned that certain ions, such as chromic ions, cobalt ions, and iron ions are small magnets. Their magnetism is due to the spin motions and orbital motions of their electrons. It has been found that many atomic nuclei are small magnets too, their magnetism being due to motions of their constituents, the protons and the neutrons. These nuclear magnets, however, are about a thousand times weaker than the ionic magnets. This makes it relatively difficult to orientate them.

Looking for possibilities to extend our metaphor of the individuals with bank accounts, I contemplated comparing the nuclei with mice which would be able to have only very small bank accounts indeed. But this comparison between mice and men would possibly grieve the nuclear physicists without giving us the satisfaction of a clear-cut parallelism. And since it is not the low temperature man's purpose to hurt the nuclear physicist, but on the contrary to please and assist him, we rather drop the metaphor now.

The properties of nuclei must be different in different directions. The emission of radioactive radiations will in general not be equal in the direction of the nuclear magnet and perpendicular to it and the probability of reaction between two nuclei must strongly depend on the mutual orientation of the two nuclear magnets. The only simple way to study this requires the orientation of nuclei in a particular direction in space. Since nuclear magnets are about a thousand times weaker than ionic magnets, this would require a ratio of magnetic field to temperature which is a thousand times higher. Thus instead of, for instance, 5000 oersted and 1°K one would need 50,000 oersted and 0.01°K. At first sight this would not seem particularly difficult. First an adiabatic demagnetization of an ionic substance would lead to 0.01°K and then a sample, containing our nuclei, should be cooled down to that temperature in the presence of the large magnetic field. However, after the demagnetization the field would be zero or small and the nuclei would have to be placed in a very large magnetic field which, as was pointed out by *Simon*, would require transport of heat over a considerable distance, which transport seems hardly feasible at so low a temperature.

In 1948 *Rose* and we independently proposed a method to get around this difficulty for the nuclei of certain magnetic ions.

The electrons in these ions bring about a field of the order of a few hundred thousand oersted acting on their own nuclei. Thus after the demagnetization, the field acting on the ions could be zero or small, while nevertheless a very high field would act on the nuclei, being amply sufficient to orientate them. A careful analysis by *Bleaney* revealed that this could be most favorably realized in a single crystal and in the autumn of 1951 the first doubtlessly positive results on nuclear alignment could be reported from Oxford and from Leiden. The alignments were carried out with the radioactive nuclei of cobalt with mass number 60. After being aligned, these nuclei first emitted an electron, thus transforming themselves into nickel nuclei, and then went over into the ground state by consecutive emission of two gamma quanta. This gamma ray emission was considerably weaker in the direction of the magnet than perpendicular to it, which was an agreement with conclusions drawn by *Deutsch* from the angular correlation of the two gamma quanta. It was possible to evaluate the strength of the radioactive cobalt nucleus and attempts are being made to determine its sign too.

It will be possible to investigate a few more nuclei of paramagnetic ions, but for other nuclei one will have to rely upon extremely large external magnetic fields, combined with rather low temperatures. The installation of very powerful electromagnets in different low temperature institutes (another effective way to reduce available cash) should also be seen in this light.

It has been mentioned several times already that the transmission and the transport of energy become very bad at very low temperatures and this is because the heat waves, which have to do the transport, have almost died out.

I am afraid that our metaphor, in which the low temperature physicist was introduced as the man who does not hesitate to apply the most radical and unscrupulous methods in order to reduce the cash reserves of his clients and friends, has somewhat affected the esteem in which he was held by those who did not really know him and the sympathy to which he hoped to be entitled.

For sympathy is what he really wants since he is faced with the threat that his restless drive to lower temperature is soon going to come to its end. It is, in fact, already now apparent that the

greatly reduced thermal transmission and thermal conductivity permit the persistence of widely different temperatures between points a few millimeters apart in a single crystal. And unless relief is brought by a new heat conducting device applicable at temperatures of a few millidegrees Kelvin, his drive to always lower temperatures will very soon be checked, not because he cannot invent and apply refined methods to reduce the temperature, but because temperature is losing its essential quality of equalizing itself because the thermometer refuses to accept the temperature of the bath and one half of a sample can no longer be cooled by the other half. All he can do is to ascribe different temperatures not only to the different regions of his sample, but also to the different elements in the same region. He thus will have to distinguish between the temperature of his nuclear magnets, of his free electrons, of his ionic magnets and of his lattice heat waves and he has to confine himself to the investigation of the vanishing rates at which energy is exchanged between elements of different temperature.

But it is not yet quite so far. Many problems of low temperature physics, among which those of superconductivity and of Helium II, remain to be solved; several further applications may be invented and developed. And also the study of the rates at which energy may be exchanged between one element and the other may give plenty of work to at least one more generation of low temperature physicists.